

Figure 7-15. Spreader Type Stoker-fired Boiler - Continuous Ash Discharge Grate

Source: Reference 206.

Conversely, in underfeed stokers, crushed coal is forced upward onto the fuel bed from below by mechanical rams or screw conveyors.^{206,208}

Benzene Emissions from Utility Boilers

Benzene emissions from utility boilers may depend on various factors, including (1) type of fossil fuel burned, (2) type of boiler used, (3) operating conditions of the boiler, and (4) pollution control device(s) used. As described below, conditions that favor more complete combustion of the fuel generally result in lower organic emissions. Emission factors for benzene emissions from utility boilers are presented in Table 7-5.

Table 7-5 presents three benzene emission factors for two types of coal-fired boilers utilizing three types of PM/SO₂/NO_x air pollution control systems. The data show only slightly higher benzene emissions from a tangentially fired boiler than a cyclone-fired boiler firing coal, and show that there is no significant difference in benzene emissions from the different air pollution control device configurations represented.²⁰⁹

Table 7-5 also presents two emission factors for two types of natural gas-fired boilers utilizing flue gas recirculation.^{3,209,210} The data show only slightly higher emissions for the opposed-wall boiler than for the tangentially fired boiler. Additionally, the emission tests from which the emission factors were generated demonstrated that changes in unit load and excess air level did not significantly impact benzene emissions from either boiler type.²¹⁰

Control Technologies for Utility Boilers

Utility boilers are highly efficient and generally the best controlled of all combustion sources. Baghouses, ESPs, wet scrubbers, and multicyclones have been applied for PM control in the utility sector. A combination of a wet scrubber and ESP are often used to control both SO₂ and PM emissions.

TABLE 7-5. SUMMARY OF BENZENE EMISSION FACTORS FOR UTILITY BOILERS

SCC	Emission Source	Fuel Type	Control Device	Emission Factor lb/MMBtu ($\mu\text{g}/\text{J}$) ^a	Factor Rating	Reference
1-01-002-03	Cyclone boiler	Coal	Baghouse/SCR/ sulfuric acid condenser ^b	5.58×10^{-6} (2.40×10^{-6})	D	209
1-01-002-03	Cyclone boiler	Coal	Electrostatic precipitator	7.90×10^{-6} (3.40×10^{-6})	D	209
1-01-003-02	Tangentially- fired boiler	Lignite ^c	Electrostatic precipitator/ scrubber ^d	3.95×10^{-5} (1.70×10^{-5})	D	209
1-01-006-01	Opposed-wall boiler ^e	Natural gas	Flue gas recirculation	1.40×10^{-6} (6.02×10^{-7})	D	210
1-01-006-04	Tangentially- fired boiler ^e	Natural gas	Flue gas recirculation	4.00×10^{-7} (1.72×10^{-7})	D	210
1-01-009-01	Boiler	Bark ^f	Uncontrolled	3.60×10^{-3} lb/ton (1.80×10^{-3} kg/Mg) ^g	E	3

^a Factors are in lb (μg) of benzene emitted per MMBtu (J).

^b There is an SO₂ reactor prior to the condenser.

^c The lignite is pulverized and dried.

^d The scrubber is a spray tower using an alkali slurry.

^e The furnace has overfire air ports and off-stoichiometric firing.

^f The bark had a moisture of 50 percent.

^g Pound (kg) of benzene emitted per ton (Mg) of bark fired.

SCR = selective catalytic reduction.

The above control technologies are not intended to reduce benzene emissions from utility boilers. In general, emissions of organic pollutants, including benzene, are reduced by operating the furnace in such a way as to promote complete combustion of the fossil fuel(s) combusted in the furnace. Therefore, any combustion modification that increases the combustion efficiency will most likely reduce benzene emissions. The following conditions can increase combustion efficiency:²¹¹

- Adequate supply of oxygen;
- Good air/fuel mixing;
- Sufficiently high combustion temperature;
- Short combustion gas residence time; and
- Uniform fuel load (i.e., consistent combustion intensity).

7.4.2 Industrial/Commercial Sector

Industrial boilers are widely used in manufacturing, processing, mining, and refining primarily to generate process steam, electricity, or space heat at the facility. However, the industrial generation of electricity is limited, with only 10 to 15 percent of industrial boiler coal consumption and 5 to 10 percent of industrial boiler gas and oil consumption used for electricity generation.²¹² The use of industrial boilers is concentrated in four major industries: pulp and paper, primary metals, chemicals, and minerals. These industries account for 82 percent of the total firing capacity.²¹³ Commercial boilers are used by commercial establishments, medical institutions, and educational institutions to provide space heating.

In collecting survey data to support its Industrial Combustion Coordinated Rulemaking (ICCR), the EPA compiled information on a total of 69,494 combustion boiler units in the industrial and commercial sectors.²¹³ While this number likely underestimates the total population of boilers in the industrial and commercial sectors (due to unreceived survey

responses and lack of information on very small units) it provides an indication of the large number of sources included in this category.

Of the units included in the ICCR survey database, approximately 70 percent were classified in the natural gas fuel subcategory, 23 percent in the oil (distillate and residual) subcategory, and 6 percent in the coal burning subcategory. These fuel subcategory assignments are based on the units burning only greater than 90 percent of the specified fuel for that subcategory. All other units (accounting for the other 1 percent of assignments) are assigned to a subcategory of “other fossil fuel.”²¹³

Other fuels burned in industrial boilers are wood wastes, liquified petroleum gas, asphalt, and kerosene. Of these fuels, wood waste is the only non-fossil fuel discussed here because benzene emissions were not characterized for combustion of the other fuels. The burning of wood waste in boilers is confined to those industries where it is available as a byproduct. It is burned both to obtain heat energy and to alleviate possible solid waste disposal problems. Generally, bark is the major type of waste burned in pulp mills. In the lumber, furniture, and plywood industries, either a mixture of wood and bark waste or wood waste alone is most frequently burned. As of 1980, there were approximately 1,600 wood-fired boilers operating in the United States, with a total capacity of over 102,381 million Btu/hour (30,000 MW).²¹⁴

Industrial and commercial coal combustion sources are located throughout the United States, but tend to follow industry and population trends. Most of the coal-fired industrial boiler sources are located in the Midwest, Appalachian, and Southeast regions. Industrial wood-fired boilers tend to be located almost exclusively at pulp and paper, lumber products, and furniture industry facilities. These industries are concentrated in the Southeast, Gulf Coast, Appalachian, and Pacific Northwest regions. The Pacific Northwest contains many of the boilers firing salt-laden wood bark.

Trade associations such as the American Boiler Manufacturers Association in Arlington, Virginia, (703-522-7350) and the Council of Industrial Boiler Owners in Fairfax Station, Virginia, (703-250-9042) can provide information on industrial boiler locations and trends.²¹⁵

Process Description of Industrial/Commercial Boilers

Some of the same types of boilers used by the utility sector are also used by the industrial/commercial sector; however, the average boiler size used by the industrial/commercial sector is substantially smaller. Additionally, a few types of boiler designs are used only by the industrial sector. For a general description of the major subassemblies of boilers and their key thermal processes, refer to the discussion of utility boilers in Section 7.4.1 and Figure 7-11. The following two sections describe industrial/commercial boilers that fire fossil fuels and wood waste.

Fossil Fuel Combustion--All of the boilers used by the utility industry (described in Section 7.4.1) are “water-tube” boilers, which means that the water being heated flows through tubes and the hot gases circulate outside the tubes. Water-tube boilers represent the majority (57 percent) of industrial and commercial boiler capacity (70 percent of industrial boiler capacity).²¹² Water-tube boilers are used in a variety of applications, ranging from supplying large amounts of process steam to providing space heat for industrial and commercial facilities. These boilers have capacities ranging from 10 to 1,500 million Btu/hr (3 to 440 MW), averaging about 410 million Btu/hr (120 MW). The most common types of water-tube boilers used in the industrial/ commercial sector are wall-fired and stoker-fired boilers. Tangentially fired and FBC boilers are less commonly used. Refer to Section 7.4.1 for descriptions of these boiler designs.²¹³

The industrial/commercial sector also uses boilers with two other types of heat transfer methods: fire-tube and cast iron boilers. Because their benzene emissions have not been characterized, these types of boilers are only briefly described below.

In fire-tube boilers, the hot gas flows through the tubes and the water being heated circulates outside of the tubes. Fire-tube boilers are not available with capacities as large as those of water-tube boilers, but they are also used to produce process steam and space heat. Most fire-tube boilers have a capacity between 1.4 and 24.9 million Btu/hour (0.4 and 7.3 MW thermal). Most installed fire-tube boilers burn oil or gas.²¹³

In cast iron boilers, the hot gas is also contained inside the tubes, which are surrounded by the water being heated, but the units are constructed of cast iron instead of steel. Cast iron boilers are limited in size and are used only to supply space heat. Cast iron boilers range in size from less than 0.3 to 9.9 million Btu/hour (0.1 to 2.9 MW thermal).²¹³

Wood Combustion--The burning of wood waste in boilers is mostly confined to those industries where it is available as a byproduct. It is burned both to obtain heat energy and to alleviate solid waste disposal problems. Wood waste may include large pieces such as slabs, logs, and bark strips, as well as cuttings, shavings, pellets, and sawdust.²¹⁴

Various boiler firing configurations are used in burning wood waste. One common type in smaller operations is the dutch oven or extension type of furnace with a flat grate. This unit is widely used because it can burn fuels with very high moisture. Fuel is fed into the oven through apertures in a firebox and is fired in a cone-shaped pile on a flat grate. The burning is done in two stages: (1) drying and gasification, and (2) combustion of gaseous products. The first stage takes place in a cell separated from the boiler section by a bridge wall. The combustion stage takes place in the main boiler section.²¹⁴

In another type of boiler, the fuel-cell oven, fuel is dropped onto suspended fixed grates and fired in a pile. The fuel cell uses combustion air preheating and positioning of secondary and tertiary air injection ports to improve boiler efficiency.²¹⁴

In many large operations, more conventional boilers have been modified to burn wood waste. The units may include spreader stokers with traveling grates or vibrating grate

stokers, as well as tangentially fired or cyclone-fired boilers (see Section 7.4.1 for descriptions of these types of boilers). The most widely used of these configurations is the spreader stoker, which can burn dry or wet wood. Fuel is dropped in front of an air jet that casts the fuel out over a moving grate. The burning is done in three stages: (1) drying, (2) distillation and burning of volatile matter, and (3) burning of fixed carbon. Natural gas or oil is often fired as auxiliary fuel. This is done to maintain constant steam when the wood supply fluctuates or to provide more steam than can be generated from the wood supply alone.²¹⁴

Sander dust is often burned in various boiler types at plywood, particle board, and furniture plants. Sander dust contains fine wood particles with low moisture content (less than 20 percent by weight). It is fired in a flaming horizontal torch, usually with natural gas as an ignition aid or supplementary fuel.²¹⁴

A recent development in wood firing is the FBC boiler. Refer to Section 7.4.1 for a description of this boiler type. Because of the large thermal mass represented by the hot inert bed particles, FBCs can handle fuels with high moisture content (up to 70 percent, total basis). Fluidized beds can also handle dirty fuels (up to 30 percent inert material). Wood material is pyrolyzed more quickly in a fluidized bed than on a grate because of its immediate contact with hot bed material. Combustion is rapid and results in nearly complete combustion of organic matter, minimizing emissions of unburned organic compounds.²¹⁴

Benzene Emissions from Industrial/Commercial Boilers

Benzene emissions from industrial/commercial boilers may depend on various factors, including (1) type of fuel burned, (2) type of boiler used, (3) operating conditions of the boiler, and (4) pollution control device(s) used. Conditions that favor more complete combustion of the fuel generally result in lower organic emissions. Additionally, the organic emissions potential of wood combustion is generally thought to be greater than that of fossil fuel combustion because wood waste has a lower heating value, which may decrease

combustion efficiency. Emission factors for benzene emissions from industrial and commercial/institutional boilers are presented in Table 7-6.^{3,216-220}

Table 7-6 presents emission factors primarily for wood waste combustion. Additionally a few emission factors are presented for fossil fuel (residual oil and coke/coal) and process gas (landfill gas and POTW digester gas) combustion. Most of the emission factors represent emissions from a non-specified type of boiler. Only two boiler types are specified (FBC and spreader-stoker). Additionally, the benzene emission factors presented are emissions following various types of PM and SO₂ emission control systems.

In most cases, Table 7-6 specifies the type of wood waste associated with the emission factors for wood combustion boilers. The composition of wood waste may have an impact on benzene emissions. The composition of wood waste depends largely on the industry from which it originates. Pulping operations, for example, produce great quantities of bark that may contain more than 70 percent by weight moisture, along with sand and other noncombustibles. Because of this, bark boilers in pulp mills may emit considerable amounts of organic compounds to the atmosphere unless they are well controlled. On the other hand, some operations, such as furniture manufacturing, produce a clean, dry wood waste, 5 to 50 percent by weight moisture, with relatively low organic emissions when properly burned. Still other operations, such as sawmills, burn a varying mixture of bark and wood waste that results in particulate emissions somewhere between those of pulp mills and furniture manufacturing. Additionally, when fossil fuels are co-fired with wood waste, the combustion efficiency is typically improved; therefore, organic emissions may decrease.²¹⁵

The type of boiler, as well as its operation, affect combustion efficiency and emissions. Wood-fired boilers require a sufficiently large refractory surface to ensure proper drying of high-moisture-content wood waste prior to combustion. Adequately dried fuel is necessary to avoid a decrease in combustion temperatures, which may increase organic emissions because of incomplete combustion.²¹⁵

TABLE 7-6. SUMMARY OF BENZENE EMISSION FACTORS FOR INDUSTRIAL
AND COMMERCIAL/INSTITUTIONAL BOILERS

SCC	Emission Source	Fuel Type	Control Device	Emission Factor lb/MMBtu ($\mu\text{g}/\text{J}$) ^a	Factor Rating	Reference
1-02-004-01	Boiler	No. 6 fuel oil	Uncontrolled	9.38×10^{-5} (4.04×10^{-5})	D	216
1-02-007-99	Boiler	Landfill gas	Uncontrolled	3.78×10^{-4} (1.63×10^{-4})	D	3
1-02-008-04	Boiler	Coke and coal	Baghouse	2.68×10^{-5} (1.15×10^{-5})	D	217
1-02-009-01	Boiler	Bark ^b	ESP	6.90×10^{-4} (2.97×10^{-4})	E	3
1-02-009-03	Boiler	Wood ^b	Wet Scrubber	4.20×10^{-3} (1.81×10^{-3})	E	3
1-02-009-03	Boiler	Wood ^c	Multiple cyclone ^d /ESP	5.12×10^{-4} (2.20×10^{-4})	E	3
1-02-009-03	Boiler	Wood ^e	Multiple cyclone ^d	1.04×10^{-3} (4.46×10^{-4})	E	3
1-02-009-03	FBC Boiler	Wood ^f	Multiple cyclone ^d /ESP	2.70×10^{-5g} (1.16×10^{-5})	E	3
1-02-009-05	Boiler	Wood and bark ^h	Multiple cyclone ^d /wet scrubber	1.01×10^{-3} (4.35×10^{-4})	E	3
1-02-009-06	Spreader-stoker boiler	Wood ⁱ	Multiple cyclone ^j	2.43×10^{-4} (1.05×10^{-4})	D	218

(continued)

TABLE 7-6. CONTINUED

SCC	Emission Source	Fuel Type	Control Device	Emission Factor lb/MMBtu ($\mu\text{g}/\text{J}$) ^a	Factor Rating	Reference
1-02-009-06	Spreader-stoker boiler	Wood	Mechanical dust collector	1.67×10^{-4} (7.18×10^{-5})	D	219
1-02-012-01	Boiler	Almond and wood	Baghouse	5.29×10^{-3} (2.28×10^{-3})	D	220
1-03-007-01	Boiler	POTW digester gas	Uncontrolled	3.50×10^{-3} (1.50×10^{-3})	C	3

^a Factors are in lb (μg) of benzene emitted per MMBtu (J).

^b Redwood and fir.

^c Fir, pine, and cedar hog-fuel and chips.

^d Without flyash reinjection.

^e Based on boilers firing sander dust fuel, hog-wood fir, and pine/fir chips.

^f Pine and fir chips.

^g Based on detection limit.

^h Sugar pine sawdust with moisture content of 60 percent.

ⁱ Hog-wood red oak and aspen, 34 percent moisture.

^j With flash reinjection.

POTW = publically owned treatment works.

ESP = electrostatic precipitator.

Control Technologies for Industrial/Commercial Boilers

Control techniques for reducing benzene emissions from industrial and commercial boilers are similar to those used for utility boilers. Refer to Section 7.4.1 for a discussion of control techniques also applicable to commercial and industrial boilers.

In Section 7.4.1, various operating conditions are listed that contribute to the combustion efficiency of a boiler (e.g., oxygen supply, good air/fuel mixing, and temperature). It has been demonstrated for a spreader-stoker boiler firing wood that benzene emissions are an order of magnitude lower under good firing conditions than under poor firing conditions (when the boiler was in an unsteady or upset condition). It has also been shown that the ratio of overfire to underfire air plays an important role in benzene emissions. Based on recent test results, the speculation is that if the balance of combustion air heavily favors underfire air, there is insufficient combustion air in the upper furnace to complete the combustion of PICs (including benzene). Conversely, with excess overfire air, the flame-quenching effect of too much combustion air in the upper furnace appears to suppress the combustion of PICs at that stage of the combustion process.²¹⁸

7.4.3 Residential Sector

The residential sector includes furnaces and boilers burning coal, oil, and natural gas, stoves and fireplaces burning wood, and kerosene heaters. All of these units are designed to heat individual homes. Locations of residential combustion sources are tied directly to population trends. Coal consumption for residential combustion purposes occurs mainly in the Northeast, Appalachian, and Midwest regions. Residential oil consumption is greatest in the Northeast and Mid-Atlantic regions. Wood-fired residential units are generally concentrated in heavily forested areas of the United States, which reflects fuel selection based on availability and price.²¹⁵

Process Description for Residential Furnaces, Boilers, Stoves, and Fireplaces

The following sections describe the types of residential furnaces, boilers, stoves, and fireplaces that fire wood, coal, oil, natural gas, kerosene.

Wood Combustion--Residential wood combustion generally occurs in either a wood-fired stove or fireplace unit located inside the house. The following discussion describes the specific characterization of woodstoves, followed by a discussion on fireplaces.

Woodstoves are commonly used in residences as space heaters. They are used both as the primary source of residential heat and to supplement conventional heating systems. Wood stoves have varying designs based on the use or non-use of baffles and catalysts, the extent of combustion chamber sealing, and differences in air intake and exhaust systems.

The EPA has identified five different categories of wood-burning stoves based on differences in both the magnitude and the composition of the emissions:²²¹

- Conventional woodstoves;
- Noncatalytic woodstoves;
- Catalytic woodstoves;
- Pellet stoves; and
- Masonry heaters.

Within these categories, there are many variations in device design and operation.

The conventional stove category comprises all stoves that do not have catalytic combustors and are not included in the other noncatalytic categories (i.e., noncatalytic and pellet). Conventional stoves do not have any emissions reduction technology or design features and, in most cases, were manufactured before July 1, 1986. Stoves of many different

airflow designs may be included in this category, such as updraft, downdraft, crossdraft and S-flow.²²¹

Noncatalytic woodstoves are those units that do not employ catalysts but do have emissions-reducing technology or features. Typical noncatalytic design includes baffles and secondary combustion chambers.²²¹

Catalytic stoves are equipped with a ceramic or metal honeycomb device, called a combustor or converter, that is coated with a noble metal such as platinum or palladium. The catalyst material reduces the ignition temperature of the unburned VOC and CO in the exhaust gases, thus augmenting their ignition and combustion at normal stove operating temperatures. As these components burn, the temperature inside the catalyst increases to a point at which the ignition of the gases is essentially self-sustaining.²²¹

Pellet stoves are those fueled with pellets of sawdust, wood products, and other biomass materials pressed into manageable shapes and sizes. These stoves have active air flow systems and unique grate design to accommodate this type of fuel. Some pellet stove models are subject to the 1988 NSPS; others are exempt because of their high air-to-fuel ratio (greater than 35-to-1).²²¹

Masonry heaters are large, enclosed chambers made of masonry products or a combination of masonry products and ceramic materials. These devices are exempt from the 1988 NSPS because of their weight (greater than 800 kg). Masonry heaters are gaining popularity as a cleaner-burning and heat-efficient form of primary and supplemental heat, relative to some other types of wood heaters. In a masonry heater, a complete charge of wood is burned in a relatively short period of time. The use of masonry materials promotes heat transfer. Thus, radiant heat from the heater warms the surrounding area for many hours after the fire has burned out.²²¹

Fireplaces are used primarily for aesthetic effects and secondarily as a supplemental heating source in houses and other dwellings. Wood is the most common fuel for fireplaces, but coal and densified wood “logs” may also be burned.²²² The user intermittently adds fuel to the fire by hand.

Fireplaces can be divided into two broad categories: (1) masonry (generally brick and/or stone, assembled on site, and integral to a structure) and (2) prefabricated (usually metal, installed on site as a package with appropriate duct work). Masonry fireplaces typically have large, fixed openings to the fire bed and dampers above the combustion area in the chimney to limit room air and heat losses when the fireplace is not being used. Some masonry fireplaces are designed or retrofitted with doors and louvers to reduce the intake of combustion air during use.²²²

Prefabricated fireplaces are commonly equipped with louvers and glass doors to reduce the intake of combustion air, and some are surrounded by ducts through which floor-level air is drawn by natural convection, heated, and returned to the room. Many varieties of prefabricated fireplaces are now on the market. One general class is the freestanding fireplace, the most common of which consists of an inverted sheet metal funnel and stovepipe directly above the fire bed. Another class is the “zero clearance” fireplace, an iron or heavy-gauge steel firebox lined inside with firebrick and surrounded by multiple steel walls with spaces for air circulation. Some zero clearance fireplaces can be inserted into existing masonry fireplace openings, and thus are sometimes called “inserts.” Some of these units are equipped with close-fitting doors and have operating and combustion characteristics similar to those of woodstoves.²²²

Masonry fireplaces usually heat a room by radiation, with a significant fraction of the combustion heat lost in the exhaust gases and through fireplace walls. Moreover, some of the radiant heat entering the room goes toward warming the air that is pulled into the residence to make up for that drawn up the chimney. The net effect is that masonry fireplaces are usually inefficient heating devices. Indeed, in cases where combustion is poor, where the

outside air is cold, or where the fire is allowed to smolder (thus drawing air into a residence without producing appreciable radiant heat energy), a net heat loss may occur in a residence using a fireplace.

Fireplace heating efficiency may be improved by a number of measures that either reduce the excess air rate or transfer back into the residence some of the heat that would normally be lost in the exhaust gases or through fireplace walls. As noted above, such measures are commonly incorporated into prefabricated units. As a result, the energy efficiencies of prefabricated fireplaces are slightly higher than those of masonry fireplaces.²²²

Coal Combustion--Coal is not a widely used source of fuel for residential heating purposes in the United States. Only 0.3 percent of the total coal consumption in 1990 was for residential use.²²³ However, combustion units burning coal may be sources of benzene emissions and may be important local sources in areas that have a large number of residential houses that rely on this fuel for heating.

There are a wide variety of coal-burning devices in use, including boilers, furnaces, coal-burning stoves, and wood-burning stoves that burn coal. These units may be hand fed or automatic feed. Boilers and warm-air furnaces are usually stoker-fed and are automatically controlled by a thermostat. The stove units are less sophisticated, generally hand fed, and less energy-efficient than boilers and furnaces. Coal-fired heating units are operated at low temperatures and do not efficiently combust fuel.²¹⁵ Therefore, the potential for emissions of benzene exists.

Distillate Oil Combustion--The most frequently used home heating oil in the United States is No. 2 fuel oil, otherwise referred to as distillate oil. Distillate oil is the second most important home heating fuel behind natural gas.²²⁴ The use of distillate oil-fired heating units is concentrated in the Northeast portion of the United States. Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, Vermont, Delaware, District of

Columbia, Maryland, New Jersey, New York, and Pennsylvania accounted for approximately 72 percent of the residential share of distillate oil sales.²²⁵

Residential oil-fired heating units exist in a number of design and operating variations related to burner and combustion chamber design, excess air, heating medium, etc. Residential systems typically operate only in an “on” or “off” mode, with a constant fuel firing rate, as opposed to commercial and industrial applications, where load modulation is used.²²⁶ In distillate oil-fired heating units, pressure or vaporization is used to atomize fuel oil in an effort to produce finer droplets for combustion. Finer droplets generally mean more complete combustion and less organic emissions.

When properly tuned, residential oil furnaces are relatively clean burning, especially as compared to woodstoves.²²⁴ However, another study has shown that in practice not all of the fuel oil is burned and tiny droplets escape the flame and are carried out in the exhaust.²²⁷ This study also concluded that most of the organic emissions from an oil furnace are due to the unburned oil (as opposed to soot from the combustion process), especially in the more modern burners that use a retention head burner, where over 90 percent of the carbon in the emissions was from unburned fuel.²²⁷

Natural Gas Combustion--Natural gas is the fuel most widely used for home heating purposes, with more than half of all the homes being heated through natural gas combustion. Gas-fired residential heating systems are generally less complex and easier to maintain than oil-burning units because the fuel burns more cleanly and no atomization is required. Most residential gas burners are typically of the same basic design. They use natural aspiration, where the primary air is mixed with the gas as it passes through the distribution pipes. Secondary air enters the furnace around the burners. Flue gases then pass through a heat exchanger and a stack. As with oil-fired systems, there are usually no pollution control equipment installed on gas systems, and excess air, residence time, flame retention devices, and maintenance are the key factors in the control of emissions from these units.

Kerosene Combustion--The sale and use of kerosene space heaters increased dramatically during the 1980s and they continue to be sold and used throughout the United States as supplementary and, in some cases, as primary home heating sources.²²⁸ These units are usually unvented and release emissions inside the home. There are two basic types of kerosene space heaters: convective and radiant.

Emission Factors for Residential Furnaces, Boilers, Stoves, and Fireplaces

The combustion of fossil fuels or wood in residential units is a relatively slow and low-temperature process. Studies do not indicate the cause(s) for benzene formation in the residential sector; however, the mechanism may be similar to that in industrial boilers and utility boilers. Benzene may be formed through incomplete combustion. Because combustion in the residential sector tends to be less efficient than in other sectors, the potential to form benzene may be greater.

Table 7-7 presents emission factors for uncontrolled benzene emissions from both catalytic and non-catalytic woodstoves.³ Benzene emission factors for other types of residential wood combustion sources are not presented because of limited data.

In general, emissions of benzene can vary widely depending on how the units are operated and the how emissions are measured. The following factors may affect benzene emissions measured from residential wood combustion sources:

- Unit design and degree of excess air;
- Wood type, moisture content, and other wood characteristics;
- Burn rate and stage of burn; and
- Firebox and chimney temperatures.

TABLE 7-7. SUMMARY OF BENZENE EMISSION FACTORS FOR RESIDENTIAL WOODSTOVES

AMS Code	Emission Source	Fuel Type	Control Device	Emission Factor lb/ton (kg/Mg) ^a	Factor Rating
21-04-008-030	Catalytic Woodstove	Wood	Uncontrolled	1.46 (7.30 x 10 ⁻¹)	E
21-04-008-051	Non-Catalytic Woodstove	Wood	Uncontrolled	1.94 (9.70 x 10 ⁻¹)	E

Source: Reference 3.

^a Factors are in lb (kg) of benzene emitted per ton (Mg) of wood fired.

AMS = area and mobile sources.

Control Techniques for Residential Furnaces, Boilers, Stoves, and Fireplaces

Residential combustion sources are generally not equipped with PM or gaseous pollutant control devices. In coal- and wood-fired sources, stove design and operating practice changes have been made to lower PM, hydrocarbon, and CO emissions. Changes include modified combustion air flow control, better thermal control and heat storage, and the use of combustion catalysts. Such changes may lead to reduced benzene emissions.

Woodstove emissions reduction features include baffles, secondary combustion chambers, and catalytic combustors. Catalytic combustors or convertors are similar to those used in automobiles. Woodstove control devices may lose efficiency over time. Control degradation for any stoves, including noncatalytic woodstoves, may occur as a result of deteriorated seals and gaskets, misaligned baffles and bypass mechanisms, broken refractories, or other damaged functional components.²²¹ In addition, combustion efficiencies may be affected by differences in the sealing of the chamber and control of the intake and exhaust systems.²¹⁵

7.5 STATIONARY INTERNAL COMBUSTION

Stationary internal combustion (IC) sources are grouped into two categories: reciprocating engines and gas turbines. Stationary IC engines and turbines are principally used for electricity generation and industrial applications such as natural gas processing, and oil and gas exploration, production and transmission.²²⁹

7.5.1 Reciprocating Engines

Process Description for Reciprocating Engines

Reciprocating engines may be classified into two types: spark and compression ignition (diesel). However, all reciprocating IC engines operate by the same basic process

depicted in Figure 7-16.²³⁰ A combustible mixture is first compressed in a small volume between the head of a piston and its surrounding cylinder. The mixture is then ignited and the resulting high-pressure products of combustion push the piston through the cylinder. This movement is converted from linear to rotary motion by a crankshaft. The piston returns, pushing out exhaust gases, and the cycle is repeated.²³¹

All diesel-fueled engines are compression-ignited and all gasoline and natural gas fueled engines are spark-ignited; however, natural gas can be used in a compression ignition engine, as discussed below. The two types of reciprocating IC engines, spark ignition and compression ignition, are discussed below, according to the following types of fuel: distillate oil (diesel), gasoline, and natural gas.

Distillate Oil (Diesel)--In compression ignition engines, more commonly known as diesel engines, combustion air is first compression-heated in the cylinder, and fuel is then injected into the hot air. Ignition is spontaneous because the air is above the auto-ignition temperature of the fuel. All distillate oil reciprocating engines are compression-ignited.

Diesel engines usually operate at a higher compression ratio (ratio of cylinder volume when the piston is at the bottom of its stroke to the volume when it is at the top) than spark-ignited engines because fuel is not present during compression; hence, there is no danger of premature auto-ignition. Because engine thermal efficiency rises with increasing pressure ratio (and pressure ratio varies directly with compression ratio), diesel engines are more efficient than spark-ignited engines. This increased efficiency is gained at the expense of poorer response to load changes and a heavier structure to withstand the higher pressures.²³²

The primary domestic use of large stationary diesel engines (greater than 600 hp [447 kW]) is in oil and gas exploration and production. These engines, in groups of three to five, supply mechanical power to operate drilling (rotary table), mud pumping, and hoisting equipment, and may also operate pumps or auxiliary power generators. Another frequent application of large stationary diesel engines is electricity generation for both base and standby

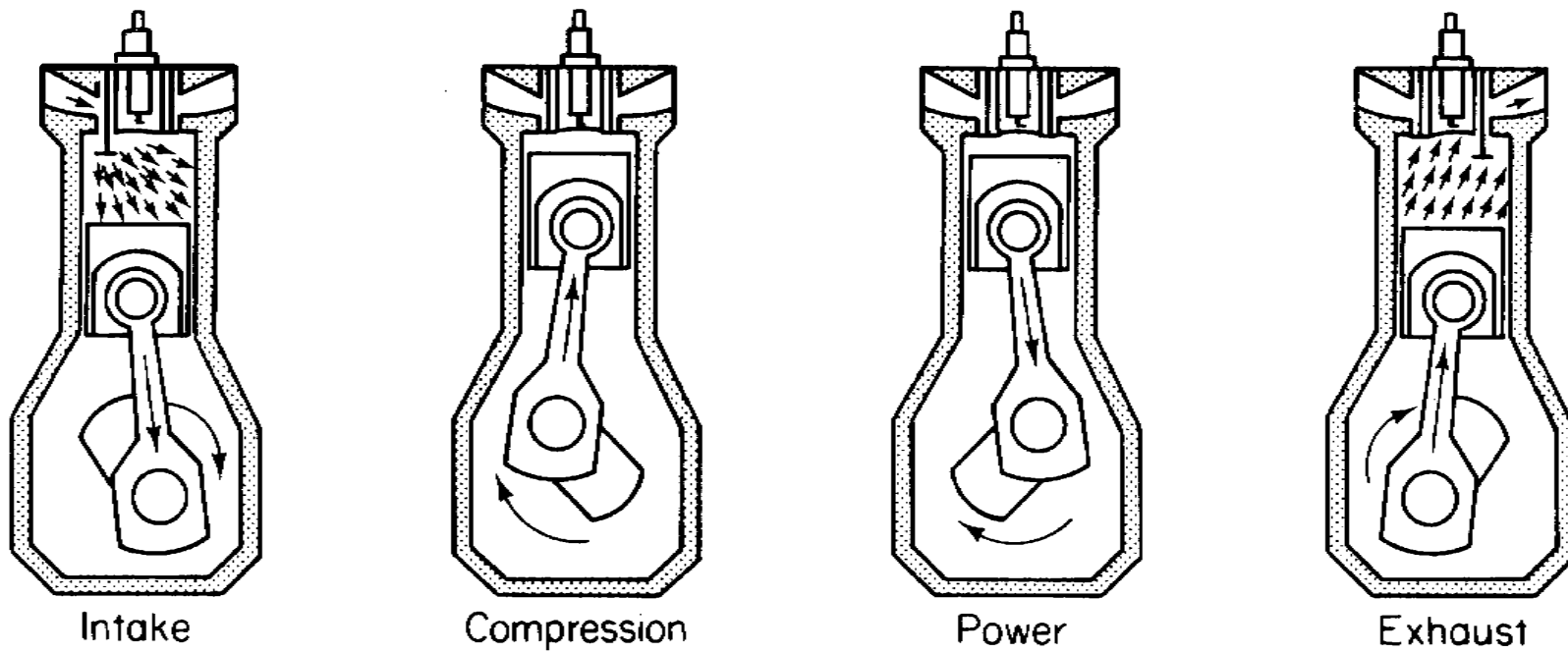


Figure 7-16. Basic Operation of Reciprocating Internal Combustion Engines

Source: Reference 230.

service. Smaller uses of large diesel engines include irrigation, hoisting, and nuclear power plant emergency cooling water pump operation. The category of smaller diesel engines (up to 600 hp [447 kW]) covers a wide variety of industrial applications such as aerial lifts, fork lifts, mobile refrigeration units, generators, pumps, industrial sweepers/scrubbers, material handling equipment (such as conveyors), and portable well-drilling equipment. The rated power of these engines can be up to 250 hp (186 kW), and substantial differences in engine duty cycles exist.²³²

Gasoline--Spark ignition initiates combustion by the spark of an electrical discharge. Usually, fuel is mixed with the air in a carburetor, but occasionally fuel is injected into the compressed air in the cylinder. All gasoline reciprocating engines are spark-ignited. Gasoline engines up to 600 hp (447 kW) can be used interchangeably with diesel IC engines in the same industrial applications described previously. As with diesel engines, substantial differences in gasoline engine duty cycles exist.²³¹

Natural Gas--Most reciprocating IC engines that use natural gas are of the spark-ignited type. As with gasoline engines, the gas is first mixed with the combustion air at an intake valve, but occasionally the fuel is injected into the compressed air in the cylinder. Natural gas can be used in a compression ignition engine, but only if a small amount of diesel fuel is injected into the compressed air/gas mixture to initiate combustion; hence the name dual-fuel engine. Dual-fuel engines were developed to obtain compression ignition performance and the economy of natural gas, using a minimum of 5 to 6 percent diesel fuel to ignite the natural gas. Large dual-fuel engines have been used almost exclusively for prime electric power generation.²³¹

Natural gas-fired stationary IC engines are also used in the natural gas industry, primarily to power compressors used for pipeline transportation, field gathering (collecting gas from wells), underground storage, and gas processing plant applications (i.e., prime movers). Pipeline engines are concentrated in the major gas-producing states (such as those along the Gulf Coast) and along the major gas pipelines.²³³

Reciprocating IC engines used in the natural gas industry are separated into three design classes: two-stroke lean burn, four-stroke lean burn, and four-stroke rich burn. Each of these have design differences that affect both baseline emissions as well as the potential for emissions control. Two-stroke engines complete the power cycle in a single engine revolution compared to two revolutions for four-stroke engines. With the two-stroke engine, the fuel/air charge is injected with the piston near the bottom of the power stroke. The valves are all covered or closed and the piston moves to the top of the cylinder compressing the charge. Following ignition and combustion, the power stroke starts with the downward movement of the piston. Exhaust ports or valves are then uncovered to remove the combustion products, and a new fuel/air charge is ingested. Two-stroke engines may be turbocharged using an exhaust-powered turbine to pressurize the charge for injection into the cylinder. Non-turbocharged engines may be either blower-scavenged or piston-scavenged to improve removal of combustion products.²³³

Four-stroke engines use a separate engine revolution for the intake/compression stroke and the power/exhaust stroke. These engines may be either naturally aspirated, using the suction from the piston to entrain the air charge, or turbocharged, using a turbine to pressurize the charge. Turbocharged units produce a higher power output for a given engine displacement, whereas naturally aspirated units have lower initial cost and maintenance. Rich-burn engines operate near the fuel/air stoichiometric limit, with exhaust excess oxygen levels less than 4 percent. Lean-burn engines may operate up to the lean flame extinction limit, with exhaust oxygen levels of 12 percent or greater.²³³

Pipeline population statistics show a nearly equal installed capacity of reciprocating IC engines and turbines. Gas turbines emit considerably smaller amounts of pollutants than do reciprocating engines; however, reciprocating engines are generally more efficient in their use of fuel. For reciprocating engines, two-stroke designs contribute approximately two-thirds of installed capacity in this industry.²³³

Benzene Emissions From Reciprocating IC Engines

Most of the pollutants from IC engines are emitted through the exhaust. However, some hydrocarbons escape from the crankcase as a result of blowby (gases that are vented from the oil pan after they have escaped from the cylinder past the piston rings) and from the fuel tank and carburetor because of evaporation. Nearly all of the hydrocarbons from diesel engines enter the atmosphere from the exhaust. Crankcase blowby is minor because hydrocarbons are not present during compression of the charge. Evaporative losses are insignificant in diesel engines because of the low volatility of diesel fuels. In general, evaporative losses are also negligible in engines using gaseous fuels because these engines receive their fuel continuously from a pipe rather than via a fuel storage tank and fuel pump.

Emission factors for uncontrolled benzene emissions from the following reciprocating engine types and fuel combinations are provided in Table 7-8:

(1) reciprocating/distillate oil and publically owned treatment works (POTW) digester gas, (2) cogeneration/distillate oil, (3) 2-cycle lean burn/natural gas, (4) large bore engine/distillate oil, and (5) large bore engine/distillate oil and gas (dual fuel). Additionally, an emission factor for benzene emissions after a non-selective catalytic reduction control device is provided for a natural gas-fired, 4-cycle, lean-burn reciprocating engine.^{3,231-233}

Control Technologies for Reciprocating Engines

Control measures for large stationary diesel engines to date have been directed mainly at limiting NO_x emissions, the primary pollutant from this group of IC engines. All of these controls are engine control techniques except for the selective catalytic reduction (SCR) technique, which is a post-combustion control. As such, all of these controls usually affect the emissions profile for other pollutants as well, and not always positively. The effectiveness of controls on a particular engine will depend on the specific design of each engine, and the effectiveness of each technique can vary considerably.

TABLE 7-8. SUMMARY OF BENZENE EMISSION FACTORS FOR RECIPROCATING ENGINES

SCC	Emission Source	Control Device(s)	Emission Factor lb/MMBtu (ng/J) ^a	Emission Factor Rating	Reference
2-02-001-02	Reciprocating distillate oil-fueled engine	Uncontrolled	9.33×10^{-4} (4.01×10^{-1})	E	3, 232
2-02-001-04	Cogeneration distillate oil-fueled engine	Uncontrolled	5.36×10^{-4} (2.30×10^{-1})	D	3
2-02-002-02	2-cycle lean burn natural gas-fueled engine	Uncontrolled	2.20×10^{-3} (9.46×10^{-1})	E	3, 233
	4-cycle lean burn natural gas-fueled engine	NSCR	7.1×10^{-4} (3.05×10^{-1})	E	233
2-02-004-01	Large bore diesel-fueled engine	Uncontrolled	7.76×10^{-4} (3.34×10^{-1})	E	3, 231
2-02-004-02	Large bore oil- and natural gas-fueled engine (dual fuel)	Uncontrolled	4.45×10^{-3} (1.91)	E	3
2-03-007-02	Reciprocating POTW digester gas-fueled engine	Uncontrolled	6.90×10^{-4} (2.97×10^{-1})	C	3

^a Factors are in lb (ng) of benzene emitted per MMBtu (J).

NSCR = nonselective catalytic reduction.

POTW = publically owned treatment works.

Other NO_x control techniques include internal/external exhaust gas recirculation (EGR), combustion chamber modification, manifold air cooling, and turbocharging. Various other emissions reduction technologies may be applicable to the smaller diesel and gasoline engines. These technologies are categorized into fuel modifications, engine modifications, and exhaust treatments.

7.5.2 Gas Turbines

Stationary gas turbines are applied in electric power generators, in gas pipeline pump and compressor drives, and in various process industries. Gas turbines (greater than 3 MW(e)) are used in electrical generation for continuous, peaking, or standby power.⁷⁹ In 1990, the actual gas-fired combustion turbine generating capacity for electric utilities was 8,524 MW.²³⁴ The current average size of electricity generation gas turbines is approximately 31 MW. Turbines are also used in industrial applications, but information was not available to estimate their installed capacity.

The same fuels used in reciprocating engines are combusted to drive gas turbines. The primary fuels used are natural gas and distillate (No. 2) fuel oil, although residual fuel oil is used in a few applications.²³⁵ The liquid fuel used must be similar in volatility to diesel fuel to produce droplets that penetrate sufficiently far into the combustion chamber to ensure efficient combustion even when a pressure atomizer is used.²³⁰

Process Description for Gas Turbines

Gas turbines are so named not because they are gas-fired, but because combustion exhaust gas drives the turbine. Unlike reciprocating engines, gas turbines operate in steady flow. As shown in Figure 7-17, a basic gas turbine consists of a compressor, a combustor, and a turbine.²³⁰ Combustion air enters the turbine through a centrifugal

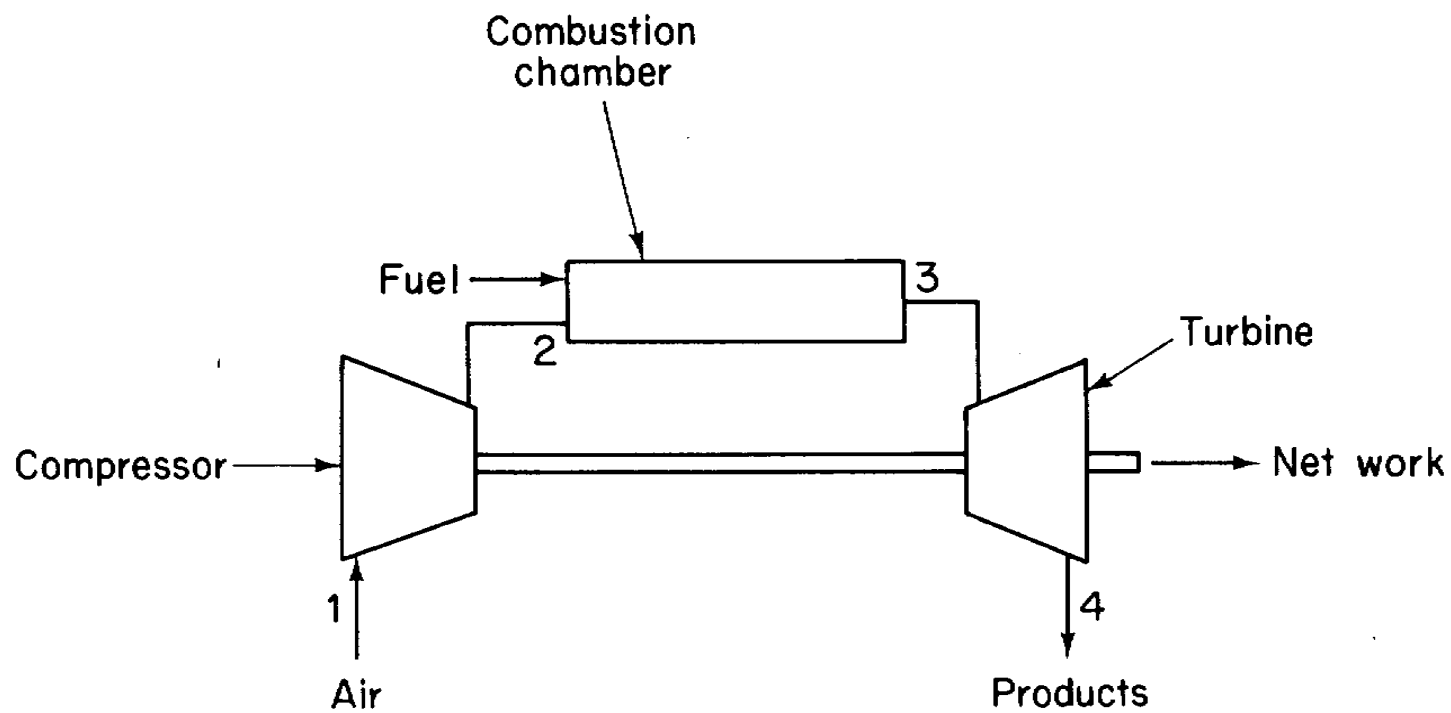


Figure 7-17. Gas Turbine Engine Configuration

Source: Reference 230.

compressor, where the pressure is raised to 5 to 30 atmospheres, depending on load and the design of the engine. Part of the air is then introduced into the primary combustion zone, into which fuel is sprayed. The fuel burns in an intense flame. Gas volume increases with combustion, so as the gases pass at high velocity through the turbine, they generate more work than is required to drive the compressor. This additional work is delivered by the turbine to a shaft to drive an electric power generator or other machinery.²³⁰

Gas turbines may be classified into three general types: simple-open-cycle, regenerative-open-cycle, and combined-cycle. In the simple-open-cycle, the hot gas discharged from the turbine is exhausted to the atmosphere. In the regenerative-open-cycle, the gas discharged from the turbine is passed through a heat exchanger to preheat the combustion air. Preheating the air increases the efficiency of the turbine. In the combined-cycle, the gas discharged from the turbine is used as auxiliary heat for a steam cycle. Regenerative-type gas turbines constitute only a very small fraction of the total gas turbine population. Identical gas turbines used in the combined-cycle and in the simple-cycle tend to exhibit the same emissions profiles. Therefore, usually only emissions from simple-cycles are evaluated.²²⁹

Benzene Emissions From Gas Turbines

Table 7-9 presents emission factors for controlled benzene emissions from two gas turbines utilized for electricity generation.³

Control Technologies for Gas Turbines

As with reciprocating engines, NO_x is the primary pollutant from gas turbines that controls have been directed at, and techniques for its control still have ramifications for the emissions profiles of other pollutants such as hydrocarbons (including benzene).

TABLE 7-9. SUMMARY OF BENZENE EMISSION FACTORS FOR GAS TURBINES

SCC	Emission Source	Control Device	Emission Factor lb/MMBtu (ng/J) ^a	Emission Factor Rating	Reference
2-01-001-01	Gas turbine fueled with distillate oil	Afterburner	9.13×10^{-5} (3.92×10^{-2})	D	3
2-01-002-01	Gas turbine fueled with natural gas	Catalytic reduction	1.10×10^{-4} (4.73×10^{-2})	E	3

^a Factors are in lb (ng) of benzene emitted per MMBtu (J).

Water/steam injection is the most prevalent NO_x control for cogeneration/combined-cycle gas turbines. Water or steam is injected with air and fuel into the turbine combustor in order to lower the peak temperatures, which in turn decreases the NO_x produced. The lower average temperature within the combustor may produce higher levels of CO and hydrocarbons as a result of incomplete combustion.²³⁵

As described in the previous section, SCR is a post-combustion control that selectively reduces NO_x by reaction of ammonia and NO on a catalytic surface to form N₂ and H₂O. Although SCR systems can be used alone, all existing applications of SCR have been used in conjunction with water/steam injection controls. For optimum SCR operation, the flue gas must be within a temperature range of 600 to 800°F (315 to 427°C), with the precise limits dependent on the catalyst. Some SCR systems also utilize a CO catalyst to give simultaneous catalytic CO/NO_x control.²³⁵

Advanced combustor designs are currently being phased into production turbines. These dry techniques decrease turbine emissions by modifying the combustion mixing, air staging, and flame stabilization to allow operation at a much leaner air/fuel ratio relative to normal operation. Operating at leaner conditions will lower peak temperatures within the primary flame zone of the combustor. The lower temperatures may also increase CO and hydrocarbon emissions.²³⁵

With the advancement of NO_x control technologies for gas turbines, the emission factors for the installed gas turbine population are quite different than for uncontrolled turbines. However, uncontrolled turbine emissions have not changed significantly. A careful review of specific turbine details should be performed before applying uncontrolled emission factors. Today, most gas turbines are controlled to meet local, State, and Federal regulations.²³⁵

7.6 SECONDARY LEAD SMELTING

In 1990, primary and secondary smelters in the United States produced 1,380,000 tons (1,255,000 Mg) of lead. Secondary lead smelters produced 946,000 tons (860,000 Mg) or about 69 percent of the total refined lead produced in 1990; primary smelters produced 434,000 tons (395,000 Mg). Table 7-10 lists U.S. secondary lead smelters according to their annual lead production capacity.²³⁶

7.6.1 Process Description

The secondary lead smelting industry produces elemental lead and lead alloys by reclaiming lead, mainly from scrap automobile batteries. Blast, reverberatory, rotary, and electric furnaces are used for smelting scrap lead and producing secondary lead. Smelting is the reduction of lead compounds to elemental lead in a high-temperature furnace. It requires higher temperatures (2,200 to 2,300 °F [1,200 to 1,260 °C]) than those required for melting elemental lead (621 °F [327 °C]). Secondary lead may be refined to produce soft lead (which is nearly pure lead) or alloyed to produce hard lead alloys. Most of the lead produced by secondary lead smelters is hard lead, which is used in the production of lead-acid batteries.²³⁶

Lead-acid batteries represent about 90 percent of the raw materials at a typical secondary lead smelter, although this percentage may vary from one plant to the next. These batteries contain approximately 18 lb (8.2 kg) of lead per battery consisting of 40 percent lead alloys and 60 percent lead oxide. Other types of lead-bearing raw materials recycled by secondary lead smelters include drosses (lead-containing byproducts of lead refining), which may be purchased from companies that perform lead alloying or refining but not smelting; battery plant scrap, such as defective grids or paste; and scrap lead, such as old pipes or roof flashing. Other scrap lead sources include cable sheathing, solder, and babbitt metal.²³⁶

As illustrated in Figure 7-18, the normal sequence of operations in a secondary lead smelter is scrap receiving, charge preparation, furnace smelting, and lead refining and

TABLE 7-10. U.S. SECONDARY LEAD SMELTERS

Smelter	Location
<u>Small-Capacity:</u> less than 22,000 tons (20,000 Mg)	
Delatte Metals	Ponchatoula, LA
General Smelting and Refining Company	College Grove, TN
Master Metals, Inc.	Cleveland, OH
Metals Control of Kansas	Hillsboro, KS
Metals Control of Oklahoma	Muskogee, OK
<u>Medium-Capacity:</u> 22,000 to 82,000 tons (20,000 to 75,000 Mg)	
Doe Run Company	Boss, MO
East Penn Manufacturing Company	Lyon Station, PA
Exide Corporation	Muncie, IN
Exide Corporation	Reading, PA
GNB, Inc.	Columbus, GA
GNB, Inc.	Frisco, TX
Gulf Coast Recycling, Inc.	Tampa, FL
Refined Metals Corporation	Beech Grove, IN
Refined Metals Corporation	Memphis, TN
RSR Corporation	City of Industry, CA
RSR Corporation	Middletown, NY
Schuylkill Metals Corporation	Forest City, MO
Tejas Resources, Inc.	Terrell, TX
<u>Large-Capacity:</u> greater than 82,000 tons (75,000 Mg)	
Gopher Smelting and Refining, Inc.	Eagan, MN
GNB, Inc.	Vernon, CA
RSR Corporation	Indianapolis, IN
Sanders Lead Company	Troy, AL
Schuylkill Metals Corporation	Baton Rouge, LA

Source: Reference 236.

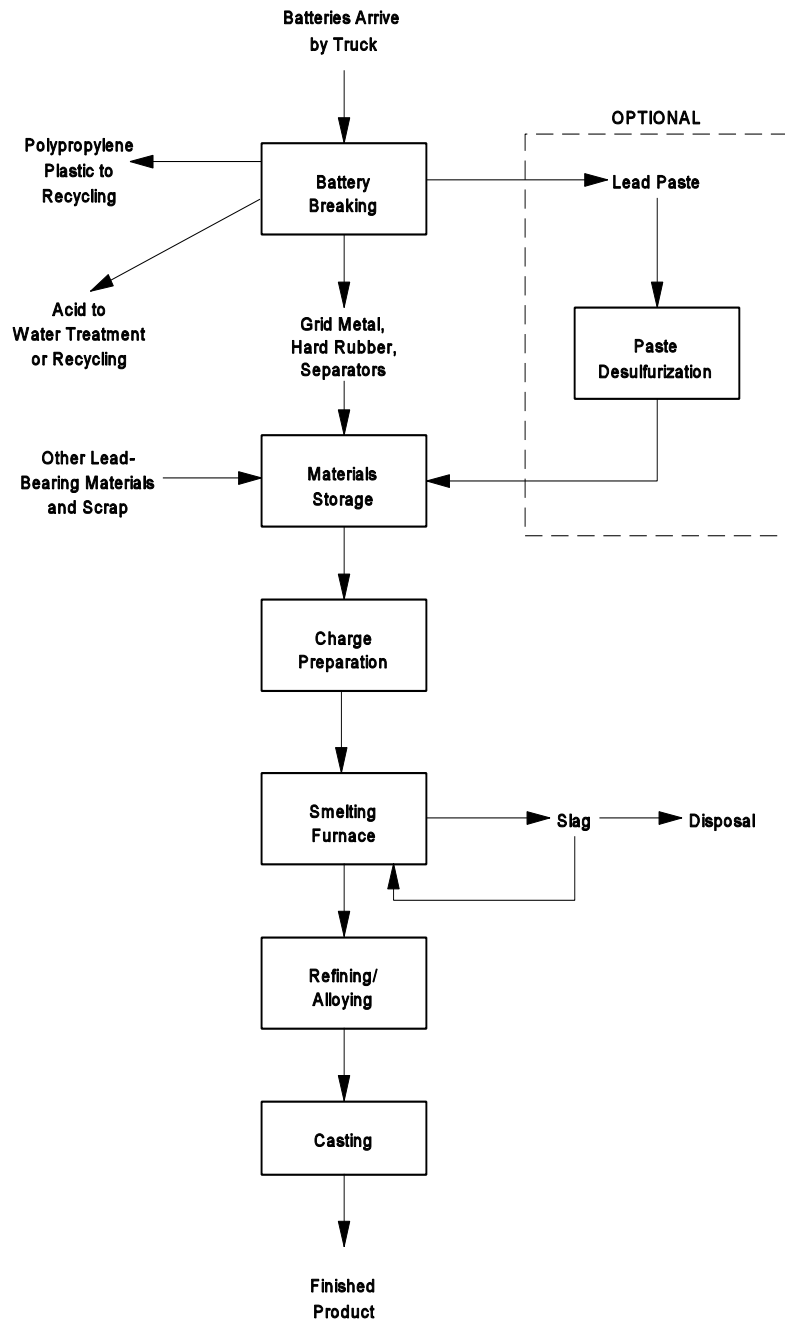


Figure 7-18. Simplified Process Flow Diagram for Secondary Lead Smelting

Source: Reference 236

alloying.²³⁶ In the majority of plants, scrap batteries are first sawed or broken open to remove the lead alloy plates and lead oxide paste material. The removal of battery covers is typically accomplished using an automatic battery feed conveyor system and a slow-speed saw. Hammermills or other crushing/shredding devices are then used to break open the battery cases. Float/sink separation systems are typically used to separate plastic battery parts, lead terminals, lead oxide paste, and rubber parts. The majority of lead smelters recover the crushed plastic materials for recycling. Rubber casings are usually landfilled.

Paste desulfurization, an optional lead recovery step used by secondary lead smelters, requires the separation of lead sulfate and lead oxide paste from the lead grid metal, polypropylene plastic cases, separators, and hard rubber battery cases. Paste desulfurization involves the chemical removal of sulfur from the lead battery paste. The process improves furnace efficiency by reducing the need for fluxing agents to reduce lead-sulfur compounds to lead metal. The process also reduces SO₂ furnace emissions. However, SO₂ emissions reduction is usually a less important consideration because many plants that perform paste desulfurization are also equipped with SO₂ scrubbers. About half of all smelters perform paste desulfurization.

After removing the lead components from the charge batteries, the lead scrap is combined with other charge materials such as refining drosses, flue dust, furnace slag, coke, limestone, sand, and scrap iron and fed to either a reverberatory, blast, rotary or electric smelting furnace. Smelting furnaces are used to produce crude lead bullion, which is refined and/or alloyed into final lead products.

Refining, the final step in secondary lead production, consists of removing impurities and adding alloying metals to the molten lead obtained from the smelting furnaces to meet a customer's specifications. Refining kettles are used for the purifying and alloying of molten lead.

Blast and reverberatory furnaces are currently the most common types of smelting furnaces in the industry, although some new plants are using rotary furnaces. There are currently about 15 reverberatory furnaces, 24 blast furnaces, 5 rotary furnaces, and 1 electric furnace in the secondary lead industry.²³⁶ The following discussion provides process descriptions of these four types of secondary lead smelters.

Reverberatory Furnaces

A reverberatory furnace (Figure 7-19) is a rectangular refractory-lined furnace.²³⁶ Reverberatory furnaces are operated on a continuous basis. Natural gas- or fuel oil-fired jets located at one end or at the sides of the furnace are used to heat the furnace and charge material to an operating temperature of about 2,000°F (1,100°C). Oxygen enrichment may be used to decrease the combustion air requirements. Reverberatory furnaces are maintained at negative pressure by an induced draft fan.

Reverberatory furnace charge materials include battery grids and paste, battery plant scrap, rerun reverberatory furnace slag, flue dust, drosses, iron, silica, and coke. A typical charge over one hour may include 9.3 tons (8.4 Mg) of grids and paste to produce 6.2 tons (5.6 Mg) of lead.²³⁶

Charge materials are often fed to a natural gas- or oil-fired rotary drying kiln, which dries the material before it reaches the furnace. The temperature of the drying kiln is about 400°F (200°C), and the drying kiln exhaust is drawn directly into the reverberatory furnace or ventilated to a control device. From the rotary drying kiln, the feed is either dropped into the top of the furnace through a charging chute, or fed into the furnace at fixed intervals with a hydraulic ram. In furnaces that use a feed chute, a hydraulic ram is often used as a stoker to move the material down the furnace.

Reverberatory furnaces are used to produce a soft (nearly pure) lead product and a lead-bearing slag. This is done by controlling the reducing conditions in the furnace so that

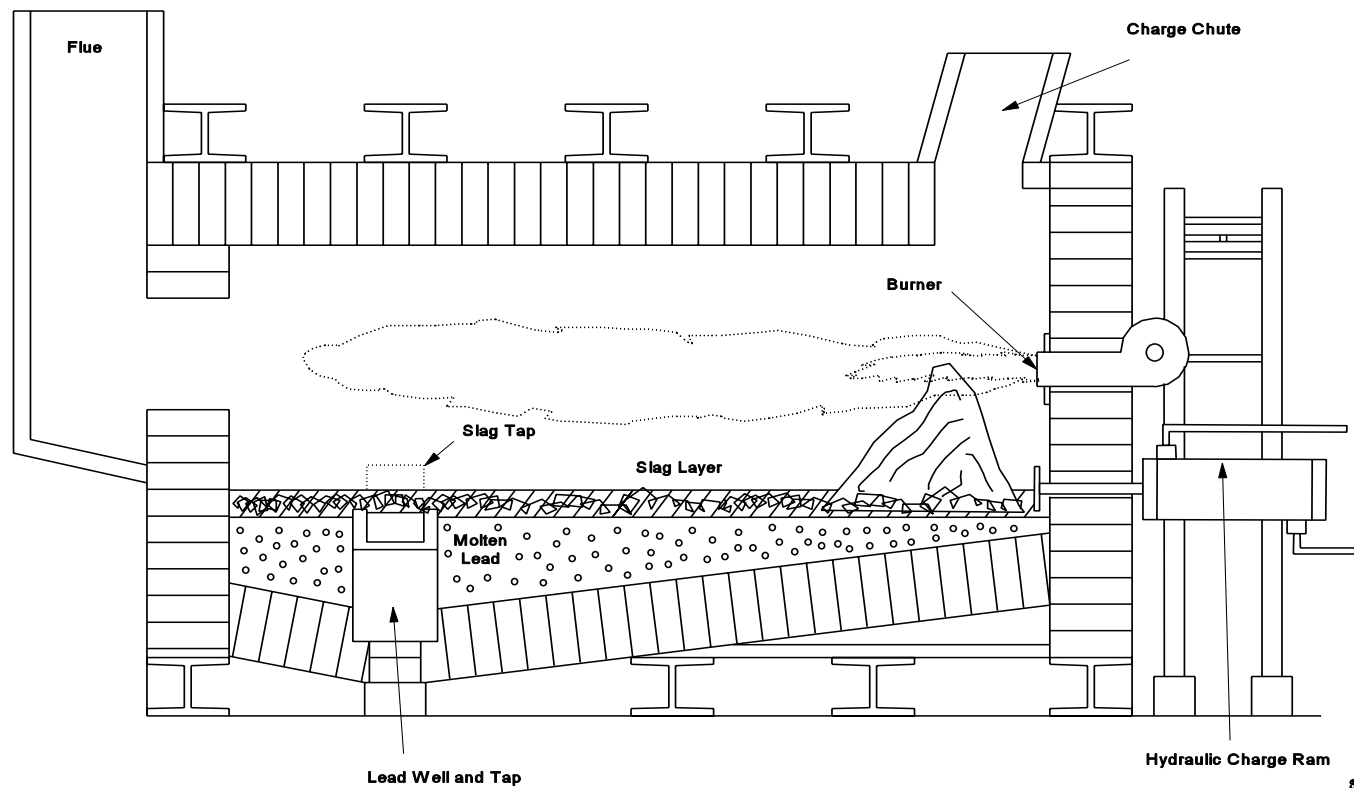
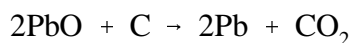


Figure 7-19. Cross-sectional View of a Typical Stationary Reverberatory Furnace

Source: Reference 236.

lead components are reduced to metallic lead bullion and the alloying elements (antimony, tin, arsenic) in the battery grids, posts, straps, and connectors are oxidized and removed in the slag. The reduction of PbSO_4 and PbO is promoted by the carbon-containing coke added to the charge material:



The PbSO_4 and PbO also react with the alloying elements to form lead bullion and oxides of the alloying elements, which are removed in the slag.

The molten lead collects in a pool at the lowest part of the hearth. Slag collects in a layer on top of this pool and retards further oxidation of the lead. The slag is made up of molten fluxing agents such as iron, silica, and lime, and typically has significant quantities of lead. Slag is usually tapped continuously and lead is tapped intermittently. The slag is tapped into a crucible. The slag tap and crucible are hooded and vented to a control device. Reverberatory furnace slag usually has a high lead content (as much as 70 percent by weight) and is used as feed material in a blast or electric furnace to recover the lead content. Reverberatory furnace slag may also be rerun through the reverberatory furnace during special slag campaigns before being sent to a blast or electric furnace. Lead may be tapped into a crucible or directly into a holding kettle. The lead tap is usually hooded and vented to a control device.²³⁶

Blast Furnaces

A blast furnace (Figure 7-20) is a vertical furnace that consists of a crucible with a vertical cylinder affixed to the top. The crucible is refractory-lined and the vertical cylinder consists of a steel water jacket. Oxygen-enriched combustion air is introduced into the furnace through tuyeres located around the base of the cylinder.

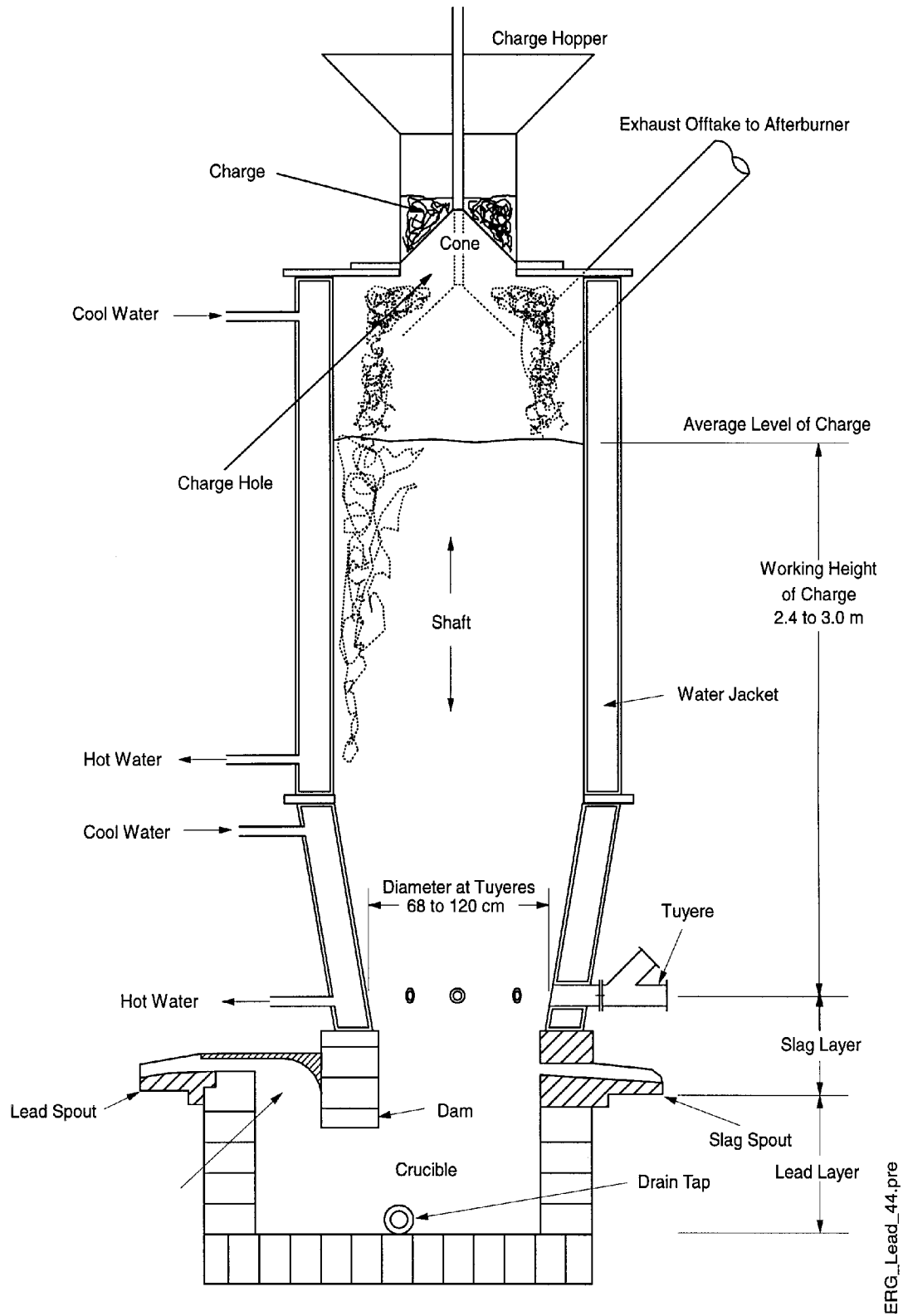


Figure 7-20. Cross Section of a Typical Blast Furnace

Charge materials are pre-weighed to ensure the proper mixture and then introduced into the top of the cylinder using a skip hoist, a conveyor, or a front-end loader. The charge fills nearly the entire cylinder. Charge material is added periodically to keep the level of the charge at a consistent working height while lead and slag are tapped from the crucible. Coke is added to the charge as the primary fuel, although natural gas jets may be used to start the combustion process. Combustion is self-sustaining as long as there is sufficient coke in the charge material. Combustion occurs in the layer of the charge nearest the tuyeres.

At plants that operate only blast furnaces, the lead-bearing charge materials may include broken battery components, drosses from the refining kettles, agglomerated flue dust, and lead-bearing slag. A typical charge over one hour may include 4.8 tons (4.4 Mg) of grids and paste, 0.3 tons (0.3 Mg) of coke, 0.1 tons (0.1 Mg) of calcium carbonate, 0.07 tons (0.06 Mg) of silica, 0.5 tons (0.4 Mg) of cast iron, and 0.2 tons (0.2 Mg) of rerun blast furnace slag, to produce 3.7 tons (3.3 Mg) of lead. At plants that also have a reverberatory furnace, the charge materials will also include lead-bearing reverberatory furnace slag.²³⁶

Blast furnaces are designed and operated to produce a hard (high alloy content) lead product by achieving more reducing furnace conditions than those typically found in a reverberatory furnace. Fluxing agents include iron, soda ash, limestone, and silica (sand). The oxidation of the iron, limestone, and silica promotes the reduction of lead compounds and prevents oxidation of the lead and other metals. The soda ash enhances the reaction of PbSO_4 and PbO with carbon from the coke to reduce these compounds to lead metal.

Lead tapped from a blast furnace has a higher content of alloying metals (up to 25 percent) than lead produced by a reverberatory furnace. In addition, much less of the lead and alloying metals are oxidized and removed in the slag, so the slag has a low metal content (e.g., 1 to 3 percent) and frequently qualifies as a nonhazardous solid waste.

Because air is introduced into the blast furnace at the tuyeres, blast furnaces are operated at positive pressure. The operating temperature at the combustion layer of the charge is between 2,200 and 2,600°F (1,200 and 1,400°C), but the temperature of the gases exiting the top of the charge material is only between 750 and 950°F (400 and 500°C).

Molten lead collects in the crucible beneath a layer of molten slag. As in a reverberatory furnace, the slag inhibits the further oxidation of the molten metal. Lead is tapped continuously and slag is tapped intermittently, slightly before it reaches the level of the tuyeres. If the tuyeres become blocked with slag, they are manually or automatically “punched” to clear the slag. A sight glass on the tuyeres allows the furnace operator to monitor the slag level and ensure that they are clear of slag. At most facilities, the slag tap is temporarily sealed with a clay plug, which is driven out to begin the flow of slag from the tap into a crucible. The slag tap and crucible are enclosed in a hood, which is vented to a control device.

A weir dam and siphon in the furnace are used to remove the lead from beneath the slag layer. Lead is tapped from a blast furnace into either a crucible or directly to a refining kettle designated as a holding kettle. The lead in the holding kettle is kept molten before being pumped to a refining kettle for refining and alloying. The lead tap on a blast furnace is hooded and vented to a control device.

Rotary Furnaces

As noted above, rotary furnaces (sometimes referred to as rotary reverberatory furnaces) (Figure 7-21) are used at only a few recently constructed secondary lead smelters in the United States.²³⁶ Rotary furnaces have two advantages over other furnace types: it is easier to adjust the relative amount of fluxing agents because the furnaces are operated on a batch rather than a continuous basis, and they achieve better mixing of the charge materials than do blast or reverberatory furnaces.